AMERICAN SOCIETY OF CIVIL ENGINEERS.

INSTITUTED 1852.

TRANSACTIONS.

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No. 811.

THE RELATION OF TENSILE STRENGTH TO COMPOSITION IN STRUCTURAL STEEL.

BY A. C. CUNNINGHAM, M. Am. Soc. C. E.

PRESENTED AT THE ANNUAL CONVENTION, 1897.

WITH DISCUSSION.

Rule.—To find the approximate tensile strength of structural steel to a base of 40 000 lbs., add 1 000 lbs. for every 0.01% of carbon, and 1 000 lbs. for every 0.01% of phosphorus, neglecting all other elements in normal steels. Radical variations between calculated and actual strength indicate mixed steels, segregation, incorrect analyses, or unusual treatment in manufacture.

The relation of composition to tensile strength in steel has been a matter of interest, speculation and investigation since the time that it has been analyzed and tested. It has long been known that steel of about 1% carbon, or 100 carbon, as it is generally called, possesses the greatest tensile strength, and that as the carbon increases or decreases from this point, there is a decrease of tensile strength. This fact is of more interest than value to the structural engineer, who cannot make use of such hard steel as this for tension members. It has also been assumed that all other elements besides carbon entering into the com-

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position of steel gave more or less strengthening effect; some were supposed to be slight, others great, and it is known in the case of manganese that radical changes take place in the nature of steel as the percentage of this element reaches certain amounts.

Years of experience have taught that carbon is the most desirable element for giving strength to steel; that definite results can be produced by varying its amount, and that the gain of strength due to its increase is accompanied with less loss of other desirable properties than is the case with any other hardener. All other elements occurring in carbon steels may be considered impurities or antidotes.

In investigating the causes of strength in steel, one naturally looks first for the strength of its base of iron and at once encounters an unknown quantity. Pure iron can be produced only in the laboratory, and even there in insufficient quantity and impossible condition for testing. The strength of pure iron has, however, been estimated and calculated to be about 38 000 lbs. per square inch.

The most notable investigations made of late years into the strengthening effects of the different elements occurring in steel have been made by Mr. Wm. R. Webster, and H. H. Campbell, M. Am. Soc. C. E., in the order named.

Mr. Webster's investigations were made upon plates of basic Bessemer steel, and consisted of assumptions subjected to trial, and variously modified to suit the conditions. He believed that all elements had a strengthening effect upon steel, and constructed tables from which, knowing the carbon, phosphorus, manganese and sulphur content of steel, its tensile strength could be calculated. His tables fitted very well the steel upon which he made his investigations, but have not proved satisfactory in the case of other steels.

The later investigations of Mr. Campbell are the most complete and scientific of any that have yet been undertaken in this line. With 3 163 tests made upon 2 x $\frac{3}{8}$-in. test bars of a known and uniform condition, arranged in 272 groups of similar conditions as to strength and composition, Mr. Campbell has, by the method of least squares, arrived at the strengthening effect of the various components of steel.*

* Mr. Campbell's work will be found in full in his book on "The Manufacture and Properties of Structural Steel."

Tables Nos. 1 and 2 at the close of the paper give one-fifth of his tests, and a comparison between them and the strength of the metal as computed by his formula and those of Mr. Webster and the author. The same data for all the 272 groups were calculated by the author, and are on file in the Library of the Society; they show the same comparative relations between actual and calculated strengths as the abridged tables.

Mr. Campbell's conclusions are as follows:

First.—The strength of pure iron, as far as it can be determined from the strength of steel, is about 38 000 or 39 000 lbs. per square inch.

Second.—An increase of 0.01% of carbon raises the tensile strength of acid steel about 1 210 lbs. per square inch, and that of basic steel about 950 lbs.

Third.—An increase of 0.01% of manganese has very little effect on acid steel, unless the content exceeds 0.60%, but it raises the strength of basic steel about 85 lbs. per square inch.

Fourth.—An increase of 0.01% of phosphorus raises the tensile strength of acid steel about 890 lbs. per square inch, and that of basic steel about 1 050 lbs.

Fifth.—The following formulas will give the ultimate strength of ordinary open-hearth steel in pounds per square inch, the carbon, manganese and phosphorus being expressed in units of 0.001%, and a value being given to R in accordance with the conditions of rolling and the thickness of the piece.

Formula for Acid Steel:

$$38\,600 + 121 \text{ carbon} + 89 \text{ phos.} + R = \text{tensile strength.}$$

Formula for Basic Steel:

$$37\,430 + 95 \text{ carbon} + 8.5 \text{ mang.} + 105 \text{ phos.} + R = \text{tensile strength.}$$

Sixth.—The metals from which these data were derived were ordinary structural steels ranging from 0.02 to 0.35% of carbon, and it is not expected that the formulas are applicable to higher steels or to special alloys.

Seventh.—A considerable difference may be found between steels which apparently are of the same composition, and which, as far as known, have been made under the same conditions.

Eighth.—In the case of acid steel, an increase in manganese above 0.6% will raise the tensile strength above the amount indicated by the formula, the increment being quite marked when a content of 0.8 is exceeded.

Ninth.—In steels containing from 0.3% to 0.5% of carbon, the value of the metalloids is fully as great as with the lower steels, while the presence of silicon in such metal in proportions greater than 0.15% seems to enhance the strengthening effect of carbon.

Tenth.—In steels containing less than 0.25% of carbon, the effect of small proportions of silicon upon the ultimate strength is inappreciable.

Eleventh.—Sulphur in ordinary proportions exerts no appreciable influence upon the tensile strength.

Twelfth.—Both acid and basic steels containing less than 0.3% of manganese give an actual strength greater than is shown by the formula, and when this is taken with the abnormal strength of unusually pure metal used in certain tests,* it is indicated that oxide of iron raises the ultimate strength.

Up to the present time the relation of tensile strength to composition has been, at the most, a matter of passing interest to the engineer. A test report showing 30 carbon and 58 000 lbs. tensile strength for one test, and 15 carbon and 60 000 lbs. for another might cause some wonderment on the part of the engineer who received it, but until recent times the chemist and his work has seldom been questioned.

The formulas deduced by Mr. Campbell offer a check on the analysis and the tensile test of steel. They are likely to prove of more value to the steel-maker than to the engineer, for they can not be retained in the memory of one having only an occasional use for them, and their application to a report of a hundred tests would be a tedious operation. A consideration of the work previously done in this line has led the author to the adoption of the rule given at the head of this paper for comparing analyses with tensile tests.

This rule is so simple that a few trials will permanently impress it on the memory. The operation may be made mentally with great rapidity, and, as far as tried, is equally applicable to all kinds and makes of steel.

* "See Manufacture and Properties of Structural Steel," Table No. 131, Group 198.

TABLE No. 1.—Acid Open-Hearth Steel.

Number of group.	Average Analysis. Percentage of.				Average actual ultimate pounds per square inch.	Campbell.		Webster.		Cunningham.	
	Carbon by combustion.	Phosphorus.	Manganese.	Sulphur.		Calculated ultimate pounds per square inch.	Difference.	Calculated ultimate pounds per square inch.	Difference.	Calculated ultimate pounds per square inch.	Difference.
1..	.061	.069	.29	.071	54 700	52 120	— 2 580	55 400	+ 700	53 000	— 1 700
6..	.087	.060	.33	.043	55 470	54 470	— 1 000	56 940	+ 1 470	54 700	— 770
11..	.096	.075	.25	.060	57 200	56 890	— 310	59 150	+ 2 260	57 100	— 100
16..	.117	.556	.39	.028	56 950	57 740	+ 790	60 790	+ 3 840	57 300	+ 350
21..	.125	.047	.41	.032	56 960	57 910	+ 950	61 340	+ 4 380	57 200	+ 240
26..	.130	.053	.40	.042	59 170	59 050	— 120	62 740	+ 3 570	58 300	— 870
31..	.143	.099	.39	.065	62 830	64 710	+ 1 880	71 640	+ 8 810	64 200	+ 1 370
36..	.155	.069	.41	.034	60 940	63 500	+ 2 560	67 690	+ 6 750	62 400	+ 1 460
41..	.170	.074	.43	.046	64 840	65 760	+ 920	70 920	+ 6 080	64 400	— 440
46..	.207	.088	.41	.047	69 410	71 480	+ 2 070	76 140	+ 6 739	69 500	+ 90
51..	.229	.065	.50	.032	70 810	72 090	+ 1 280	74 400	+ 3 590	69 400	— 1 410
56..	.424	.043	.57	.031	94 470	93 730	— 740	.....	.....	86 700	— 7 770
61..	.113	.061	.43	.038	57 140	57 700	+ 560	61 070	+ 3 930	57 400	+ 260
66..	.116	.082	.50	.069	60 870	59 930	— 940	67 300	+ 6 430	59 800	— 1 070
71..	.118	.075	.42	.045	59 110	59 550	+ 440	64 480	+ 5 370	59 300	+ 190
76..	.119	.065	.43	.028	61 020	58 780	— 2 240	62 570	+ 1 550	58 400	— 2 620
81..	.134	.045	.48	.035	58 820	58 820	0	62 410	+ 3 590	57 900	— 920
86..	.151	.051	.64	.033	62 650	61 410	— 1 240	67 200	+ 4 550	60 200	— 2 450
91..	.183	.027	.68	.030	65 100	63 150	— 1 950	66 100	+ 1 000	61 000	— 4 100
96..	.212	.073	.82	.039	71 870	70 750	— 1 120	82 230	+10 360	68 500	— 3 370
101..	.242	.076	.86	.049	78 020	74 650	— 3 370	85 690	+ 7 670	71 800	— 6 220
106..	.374	.057	.83	.035	90 750	88 930	— 1 820	.....	.....	83 100	— 7 650
111..	.392	.029	.63	.022	98 180	88 610	— 9 570	.....	.....	82 100	—16 080
116..	.333	.041	.65	.026	87 410	82 540	— 4 870	.....	.....	77 400	—10 010
121..	.480	.032	.69	.022	111 740	99 530	—12 210	.....	.....	91 200	—20 540
126..	.555	.109	1.13	.042	123 620	115 460	— 8 160	.....	.....	106 400	—17 220

TABLE No. 2.—Basic Open-Hearth Steel.

No. of group.	Average Analysis. Percentage of.				Average actual ultimate Pounds per square inch.	Campbell.		Webster.		Cunningham.	
	Carbon by combustion.	Phosphorus.	Manganese.	Sulphur.		Calculated ult. Pounds per square inch.	Difference.	Calculated ult. Pounds per square inch.	Difference.	Calculated ult. Pounds per square inch.	Difference.
127..	.051	.008	.25	.027	46 630	45 240	— 1 390	.....	.....	45 900	— 730
132..	.070	.009	.36	.050	47 360	48 090	+ 730	51 610	+ 4 250	47 900	+ 540
137..	.074	.021	.38	.034	49 280	49 900	+ 620	52 730	+ 3 450	49 500	+ 220
142..	.082	.014	.43	.038	50 770	50 350	— 420	53 270	+ 2 500	49 600	— 1 170
147..	.105	.012	.53	.032	52 970	53 170	+ 200	56 450	+ 3 480	51 700	— 1 270
152..	.127	.010	.43	.019	52 980	54 200	+ 1 220	56 420	+ 3 440	53 700	+ 720
157	.144	.013	.30	.037	55 260	55 030	— 230	56 800	+ 1 540	55 700	+ 440
162..	.165	.021	.41	.051	57 220	58 800	+ 1 580	62 640	+ 5 420	58 600	+ 1 380
167..	.170	.040	.42	.043	61 070	61 770	+ 700	65 630	+ 4 310	61 000	— 70
172..	.183	.008	.36	.030	57 350	58 710	+ 1 360	60 110	+ 2 760	59 100	+ 1 750
177..	.194	.023	.51	.040	61 340	62 610	+ 1 270	65 700	+ 4 360	61 700	+ 360
182..	.209	.024	.47	.053	63 220	63 800	+ 580	67 490	+ 4 270	63 300	+ 80
187..	.220	.015	.40	.018	63 560	63 300	— 260	64 100	+ 540	63 500	— 60
192..	.248	.018	.40	.033	66 220	66 280	+ 60	67 200	+ 980	66 600	+ 380
197..	.301	.017	.65	.029	76 890	73 340	— 3 550	.....	.....	71 800	+ 5 090
202..	.052	.019	.35	.054	49 010	47 340	— 1 670	.....	.....	47 100	+ 1 910
207..	.062	.015	.21	.036	48 980	46 680	— 2 300	47 570	— 1 410	47 700	— 1 280
212..	.076	.018	.41	.062	50 880	50 030	— 850	53 790	+ 2 910	49 400	— 1 480
217..	.084	.021	.25	.033	50 900	49 740	— 1 160	50 300	— 600	50 500	— 400
222..	.094	.046	.43	.036	54 800	54 840	+ 40	56 820	+ 2 020	54 000	— 800
227..	.103	.027	.44	.064	54 950	53 790	— 1 160	57 610	+ 2 660	53 000	— 1 950
232..	.117	.053	.46	.035	57 210	58 020	+ 810	62 120	+ 4 910	57 000	— 210
237..	.125	.036	.54	.060	58 790	57 680	— 1 110	63 000	+ 6 210	56 100	— 2 690
242..	.134	055	.51	.036	59 110	60 270	+ 1 160	64 100	+ 4 990	58 900	— 210
247..	.144	.028	.52	.034	58 970	58 470	— 500	61 950	+ 2 980	57 200	— 1 270
252..	.153	.012	.46	.027	58 970	57 130	— 1 840	59 020	+ 50	56 500	— 2 470
257..	.173	.021	.53	.021	60 810	60 570	— 240	62 600	+ 1 790	59 400	— 1 410
262..	.190	.047	.72	.037	66 480	66 530	+ 50	74 510	+ 7 930	63 700	— 2 780
267..	.215	.011	.42	.024	63 470	62 580	— 890	64 630	+ 1 160	62 600	— 870
272..	.338	.017	.62	.026	77 950	76 600	— 1 350	.....	.....	75 500	— 2 450

DISCUSSION.

1 Metcalf. WILLIAM METCALF, Past-President Am. Soc. C. E.—There has been for many years a very strong belief that there is some relation between the strength of any piece of iron and its composition, which would be a guide for estimating the strength of the metal from its chemical composition. Engineers should be very grateful to Messrs. Webster and Campbell for the extraordinary amount of work they have done in trying to work out such an exceedingly complicated and difficult problem. Their work is admirable, and may be very useful if it is not applied practically until it has been carried much farther. If it is considered that the manufacturer can vary the strength of steel by manipulation from 50% to 100% one way or the other, it is evident that the formulas are not safe guides for determining the strength of steel of a given composition. It will not do to lay aside the actual tests of material. Another difficulty in the way of the use of the formulas is the fact that they apply only to the grade of steel with which the experiments were conducted. Mr. Campbell states that this was the mild structural steel he was making.

There is a statement in the paper, quoted from Mr. Campbell's book, that certain tests indicate that oxide of iron raises the ultimate strength of steel. It was the speaker's experience that there is no element with which the manufacturer has to deal which is so treacherous and troublesome as oxygen, and there is nothing which makes steel so thoroughly rotten as its presence.

Mr. Waddell states in his correspondence on this paper that steel of 75 000 lbs. is fully up to or beyond the limit of the uses of a structural engineer. However, engineers are already using, perhaps not in large structures, but in very important places, steel of from 95 000 to 100 000 lbs. tensile strength, 40 000 to 50 000 lbs. elastic limit, and about 15% stretch. Such steel can now be made readily, and is used largely for the wristpins, sidebars and other parts of locomotives which are subject to great strains. If it has been found that a 95 000-lb. steel with 15% stretch is the best for such service, it appears that engineers wishing strong bridge pins and similar pieces could readily obtain them of the same strength and elongation. The stresses to which wristpins and sidebars are subjected are more destructive than any coming on a bridge pin.

The speaker did not care to enter into a discussion of the formulas, because, while the work on which they are based was admirable, he hoped engineers would not use them until the investigations have been carried far enough to include, not only the composition, but also the manipulation of the material. Until that is done, and as long as a little variation in manipulation can upset by many times all the

variations given by the author's formula for the chemical elements, such formulas have no safe working value unless used in connection with the testing machine. Mr. Metcalf.

JOSEPH MAYER, M. Am. Soc. C. E.—As regards steel of high strength, members may be interested to learn that wire has been drawn during the last two years for the cables of suspension bridges which has an ultimate strength of about 200 000 lbs., an elastic limit of about 160 000 to 180 000 lbs., and an elongation of 4 per cent. That the price of such wire was not excessive is shown by its use in most of the large suspension bridges recently erected. Mr. Mayer.

CORRESPONDENCE.

H. H. CAMPBELL, M. Am. Soc. C. E.—The paper discusses at length the results of investigations made by the writer upon the influence of the metalloids usually found in steel. The full details of the calculations were published more for the benefit of the metallurgist than of the engineer. The problem was far from simple. It had been attacked by many students, and the writer does not suppose for a moment that the final answer has been given. On the contrary, it will be found that the book in which these results were published expressly states that many things are left in darkness. Instances of error will be found in the author's Table No. 1, where Group 121 shows a difference of 12 210 lbs. between the actual and the calculated weight. This discrepancy is discussed on pages 316, 317 and 318 of the writer's "Structural Steel," and it is pointed out that the law seems to fail in steels containing a combination of high silicon and high carbon. In this group the content of silicon was 0.23%, but it does not appear that the silicon itself has a direct effect upon the iron, but that it enhances the effect of the associated carbon. This, however, is theory, and is offered here only as an instance of the complexities arising during the investigation, and as showing how engineers must approach the subject with a proper feeling of respect. Mr. Campbell.

It is also necessary to note that the thickness of the material has a marked bearing on the tensile strength. This was expressed by the writer in a factor in his formula, which represented an allowance for the section and the finishing temperature. In the case of annealed work this factor would be quite important.

The author has ignored these refinements in his formula, although he is thoroughly aware of their existence and their value. He has aimed to attain simplicity and is entitled to great credit for his success. These remarks, therefore, must not be considered as a criticism of his work, but as a warning to engineers that such complications exist, a fact which the author has hardly made sufficiently prominent.

Mr. Waddell. J. A. L. WADDELL, M. Am. Soc. C. E.—The author has given to the engineering profession a very useful little formula which can be remembered readily. The tabulated figures which he presents provide a method of checking the accuracy of, not only his formula, but also that of the formulas of Messrs. Campbell and Webster. The following average errors of the three formulas have been computed therefrom:

FOR ACID STEEL.

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	1 272 lbs.	4 022 lbs.	566 lbs.
Minus errors	3 073 "	None.	5 549 "
All errors	2 446 "	4 022 lbs.	4 203 "

FOR BASIC STEEL.

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	742 lbs.	3 288 lbs.	1 000 lbs.
Minus errors	1 183 "	1 005 "	1 320 "
All errors	977 "	3 112 "	1 215 "

AVERAGE FOR ACID AND BASIC STEELS.
(Mean from two preceding tables.)

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	1 007 lbs.	3 955 lbs.	783 lbs.
Minus errors	2 128 "	503 "	3 435 "
All errors	1 712 "	3 867 "	2 709 "

From these tables it will be seen that the author's formula is less accurate than that of Mr. Campbell, but more accurate than that of Mr. Webster.

An examination of the author's two tables shows that the greatest errors in all three formulas are for the very high steels, and that the higher the steel, the greater the error.

Now, as structural engineers—if it be permissible to coin such a designation—are not interested in steel having an ultimate strength exceeding 75 000 lbs. per square inch, it would be interesting to see what are the various errors of the three formulas for steels below that

limit; consequently, the writer has prepared the following tables on that basis:

Mr. Waddell.

FOR ACID STEEL.

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	1 272 lbs.	4 461 lbs.	566 lbs.
Minus errors	1 150 "	None.	1 652 "
All errors	1 208 "	4 461 lbs.	1 251 "

FOR BASIC STEEL.

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	742 lbs.	3 288 lbs.	659 lbs.
Minus errors	1 001 "	1 005 "	1 312 "
All errors	871 "	3 112 "	1 032 "

AVERAGE FOR ACID AND BASIC STEELS.

(Mean from two preceding tables.)

Character of errors.	AVERAGE ERRORS.		
	Campbell.	Webster.	Cunningham.
Plus errors	1 007 lbs.	3 875 lbs.	613 lbs.
Minus errors	1 076 "	503 "	1 482 "
All errors	1 040 "	3 787 "	1 141 "

From the last table it will be seen that, within the ultimate limit for tensile strength of steel set by the practice of the structural engineer, the author's formula is on the average almost as accurate as the more complicated one of Mr. Campbell.

The question now arises as to whether the author's formula is theoretically as perfect as it could be made. If it were, the average plus and minus errors would be alike. For acid steel they are respectively 566 lbs. and 1 652 lbs.; for basic steel they are 659 lbs. and 1 312 lbs.; and for the average of acid and basic steels they are 613 lbs. and 1 482 lbs. These variations are not great, especially in the case of basic steel; and as that metal is used nowadays in nine cases out of ten, it is fair to conclude that the author's formula cannot be very much improved upon, considering its simple form and easily remembered constants.

Mr. Waddell. As a check on the accuracy of the formula the writer has chosen at random a file of inspectors' reports on the strength and other properties of basic steel from among the tests of some thirty odd thousand tons made for him on that metal during the last three years, and from the same has obtained the following figures, each case tabulated representing an average of six records.

Actual strength.	By formula.	Plus errors.	Minus errors.
62 900	64 500	1 600	
63 483	65 900	2 417	
64 152	65 050	898	
64 400	64 600	200	
63 827	64 150	323	
63 427	64 650	1 223	
64 252	63 800	.....	452
62 547	64 200	1 653	
64 565	64 650	85	
64 903	65 350	447	
64 163	64 950	787	
63 593	64 070	477	
63 117	63 750	633	
62 458	66 350	3 892	
62 945	63 150	205	
62 877	64 300	1 423	
61 700	64 550	2 850	
64 030	64 950	920	
67 440	66 000	.....	1 440
61 637	63 050	1 413	
62 573	63 000	427	
62 582	63 150	568	
64 327	61 550	.....	2 777
64 552	63 800	.....	752
63 590	63 950	360	
61 600	63 900	2 300	
62 742	63 200	458	
70 117	69 330	.....	787
62 780	63 800	1 020	
62 965	64 400	1 435	
63 351	64 800	1 449	
63 730	64 250	520	
64 980	66 750	1 770	
63 800	64 850	1 050	
67 087	65 350	.....	1 737
64 375	64 850	475	

The averages from the preceding table are as follows:

Plus errors average	1 109 lbs.
Minus errors average	1 324 "
All errors average	1 145 "

This is a very close coincidence with the results found for basic steel from the author's tables with all metal ruled out that exceeds in ultimate strength 75 000 lbs. per square inch. It shows also, as previously indicated, that the constants in his formula cannot well be improved upon, because the average plus error and the average minus error do not differ much numerically.

A more correct method of proving this is to take the algebraic sum of all errors and divide by the number of same. The result will show how far the formula is from perfect adjustment. Treating thus all the cases in the author's two tables, where the ultimate strength is below

75 000 lbs. per square inch, gives a negative average error of 615 lbs. A corresponding treatment of the writer's table gives a positive average error of 703 lbs. Mr. Waddell.

Treating in the same way a combination of the amended table of the author and that of the writer gives a negative average error of only 44 lbs.

This proves once more and most conclusively that, on the basis of the tests herein employed, the author's formula cannot be materially improved.

A. C. CUNNINGHAM, M. Am. Soc. C. E.—In deducing the formula with which this paper opens, the object has not been to solve a complicated and difficult metallurgical problem, but rather to provide a simple and readily applied rule, sufficiently near the truth to be of value to the engineer. Mr. Cunningham.

The application of the formula to Mr. Campbell's tables represents but a few of the many trials to which it had been previously subjected with different kinds and grades of steel made by many different manufacturers. In submitting the formula, Mr. Campbell's tables were used for its application on account of the extreme accuracy of the analyses therein contained, and for a comparison of results of various formulas. It is not intended to take the place of a tension test. Were it possible to deduce a formula which would show the exact strength of steel under all and varying conditions, we would still retain the tension test, for it shows many other and valuable properties besides the ultimate strength. The formula is intended to establish for the engineer a relation between the analysis of steel and its tension test.

It is true that varying manipulations will raise or lower the tensile strength of steel while its chemical composition remains the same, as hot or cold finishing, quenching or quick cooling, and annealing or slow cooling.

It is also true that the great bulk of steel which enters into bridges and other structures is not subject to the above influences, unless intentionally. The conditions governing the manufacture of structural steel to-day are remarkably uniform throughout this country; the amount of work put upon the steel in rolling, and its finishing temperature and rate of final cooling, differ but slightly between the various mills, and still less in each individual mill. Neither does the chemical composition of structural steel vary to any great extent between the different mills, and it is safe to say that the principal constituents of most of the steel made will be between the following limits.

For Acid Open-Hearth:

Carb., .10 to .30; phos., .05 to .10; mang., .30 to .60; sulph., .04 to .07.

For Basic Open-Hearth:

Carb., .10 to .30; phos., .02 to .06; mang., .20 to .50; sulph., .03 to .06.

Mr. Cunningham.

When it is considered also that 80 or 90% of the material entering into structures is between the thickness of $\frac{3}{8}$ and $\frac{3}{4}$ in., the difficulty of constructing a formula that shall give a relation between the analysis and the tensile strength for the great majority of cases is not so great as at first appears.

While physical manipulations will change the normal or standard relations between the composition of steel and its tensile strength, there are other conditions, of even more importance to the engineer, which will also change them. These conditions are segregation or the uneven distribution of the constituents of steel, and incorrect analyses. Under the latter may be included the accidental or intentional substitution of one kind of steel for another, or of one cast of steel for another.

When a formula shows a close relation between composition and strength in one hundred cases, and differs materially in the one hundred and first, it is safe to assume that in this case there is no relation between the given composition and the strength of the steel, and it is time for investigation.

When the approximate correctness of a formula for calculating the strength of steel from its composition has once been established, such a formula is only specially valuable to the engineer when it indicates a radical variation between the calculated and actual strength, for then, as stated in the opening rule, it indicates mixed steels, segregation, incorrect analyses or unusual treatment, all of which are conditions undesirable to the engineer.

Had Mr. Metcalf understood that this formula was not intended to take the place of a tension test nor to supplant any of the established chemical or physical tests, but rather to draw them into closer relation and demonstrate that manipulation and other things will greatly change the strength of steel, it is believed that, instead of warning engineers against this and other formulas, he would have recommended their thorough trial to demonstrate their use or uselessness. Thanks are due to Mr. Waddell for his careful and extensive trial of the formula, and his success with it shows the extreme care which he has exercised in the selection and testing of his steel.

The analysis of steel which reaches the engineer, and on the strength of which the manufacturer rolls it into finished sections, is the "heat" or "cast" analysis, and is made on a small sample taken from the molten steel when cast. This cast analysis represents the average amount of the various elements contained in the steel. Now, it is not at all unusual for segregation to redistribute the elements in a cooling ingot so that they may vary in different parts as much as 25% above or below the average, and it is not so uncommon as to cause wonderment to find them varying 100 per cent.

A variation of 25% in the segregating elements is not harmful in an

ordinarily good steel, while a variation of over 50% will reduce parts of the steel to a very common quality, and a variation of 100% is likely to make the highly segregated portions dangerous for any important use. Mr. Cunningham.

As the segregating elements in the engineer's tension test are liable to vary 25% or more from the cast analysis, an allowance must be made for variation between the actual strength and that calculated by the formula from the "cast" or average analysis. For ordinarily good steels, the not dangerous variation of 25% corresponds to a variation between the calculated and actual strength of about 5 000 lbs. above or below.

For those who wish to use or introduce into their specifications a formula for calculating the strength of steel, the following clause is suggested:

The tensile strength of each cast of steel shall be calculated from its cast analysis by the following formula: * * * Tension tests varying from calculated strength more than 5 000 lbs. for material between $\frac{3}{8}$ and $\frac{3}{4}$ in. in thickness, and varying more than 7 000 lbs. for other material, shall be cause for additional tests and check analyses on the cast of steel in question.

The following examples of the use of this formula, taken from actual practice, show some of its valuable applications:

Example No. 1.—A test piece from a forged pin gives an ultimate strength of 60 640 lbs. per square inch. One chemist reports the analysis of drillings from this test piece to be as follows:

.24 carbon, .053 phos., .44 mang., .033 sulphur.

Another chemist reports the analysis of the same drillings to be as follows:

.14 carbon, .051 phos., .42 mang., .024 sulphur.

Which analysis is more likely to be correct?

From the first analysis, by the rule, the ultimate would be 40 000 + 24 000 + 5 300 = 69 300 lbs., exceeding the actual ultimate by 8 660 lbs. From the second analysis, 40 000 + 14 000 + 5 100 = 59 100 lbs., being less than the actual ultimate by 1 540 lbs., from which it may be assumed that the second analysis is the more nearly correct.

Example No. 2.—The cast analysis of a heat of steel from which a forged pin has been made is as follows:

.22 carbon, .053 phos., .40 mang., .038 sulphur.

A test piece from the circumference of this pin gives an ultimate strength of 60 640 lbs., while a test piece from the axis gives an ultimate of 74 360 lbs. Is not this pin badly segregated?

From the cast analysis, by the rule, the calculated ultimate would be 40 000 + 22 000 + 5 300 = 67 300 lbs., exceeding the actual ultimate at the circumference by 6 660 lbs., and being less than the actual ultimate at the axis by 7 060 lbs. Drillings from the test piece at the cir-

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cumference analyzed as follows: .14 carbon, .051 phos., .42 mang., .024 sulphur, which indicates an ultimate of 59 100 lbs.

Drillings from the test piece at the axis analyzed as follows: .22 carbon, .091 phos., .47 mang., .077 sulphur.

Which indicates an ultimate of 71 100 lbs. There is, therefore, a great segregation of carbon, phosphorus and sulphur in this pin, as indicated by the variation of actual ultimates from the calculated ultimate of the cast analysis.

Example No. 3.—A 3 x 3 x $\frac{3}{8}$-in. Bessemer steel angle made from a blow containing .40 carbon gives on test an ultimate strength of 91 680 lbs. per square inch. What is the probable phosphorus content of this angle?

The ultimate strength, less the base and the hardness due to carbon, gives the hardness due to phosphorus, which, divided by 1 000, gives the probable phosphorus content.

91 680 — (40 000 + 40 000) = 11 680 = $\pm$ .12 phos.

Analysis of this angle gave carbon .39 and phos. .142, corresponding to a calculated ultimate of 93 200 lbs., and differing from the actual ultimate by only 1 520 lbs.

Example No. 4.—A test from the edge of a 30 x $\frac{5}{16}$-in. universal mill plate gives an ultimate strength of 59 200 lbs. per square inch, and the analysis of the test piece gives .08 carbon, .077 phos., and .040 sulphur. A test on the center line of the same plate gives an ultimate strength of 66 520 lbs. per square inch. Assuming that the segregation is confined entirely to phosphorus, and that the carbon does not change, as being the worst condition, what is the probable phosphorus content at the center of the plate?

66 520 — (40 000 + 8 000) = 18 520 = $\pm$ .18 phos. The actual analysis of the center test piece gave .09 carbon, .153 phos., and .085 sulphur.

	C.	P.	S.	Act. Ult.	Calc. Ult.	Diff.
Edge,	.08	.077	.040	59 200	55 700	3 500
Center,	.09	.153	.085	66 520	64 300	2 220

Example No. 5.—A 6 x 6 x $\frac{5}{8}$-in. angle gives an ultimate strength of 58 840 lbs. per square inch. It is supposed to be acid open-hearth steel from a cast containing .19 carbon, .046 phos., and .042 sulphur, which indicates an ultimate strength of 40 000 + 19 000 + 4 600 = 63 600 lbs. Is this a case of segregation or mixed steel? The analyses of the test piece gave .20 carbon, .009 phos., and .027 sulphur, corresponding to an ultimate of 60 900, and clearly indicating that the angle was of basic open-hearth steel.